Design and Development of a Continuous Passive Motion Device for Physiotherapeutic Treatment of Human Knee

A thesis submitted in partial fulfillment of the
Requirements for the degree of

Bachelor of Technology
In
Industrial Design
By

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Declaration

We hereby declare that this thesis is our own work and effort. Throughout this documentation wherever contributions of others are involved, every endeavour was made to acknowledge this clearly with due reference to literature. This work is being submitted for meeting the partial fulfilment for the degree of Bachelor of Technology in Industrial Design at National Institute Of Technology, Rourkela for the academic session 2011 – 2015.

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Certificate of Approval

This is to certify that the thesis entitled "**DESIGN AND DEVELOPMENT OF A CONTINUOUS PASSIVE MOTION DEVICE FOR PHYSIOTHERAPEUTIC TREATMENT OF HUMAN KNEE**" submitted to the National Institute of Technology, Rourkela by **SAMBIT GHADAI**, **Roll No. 111ID0006** and **PRANIT KUMAR PUROHIT**, **Roll No. 111ID0025** for the award of the Degree of Bachelor of Technology in Industrial Design Engineering is a record of bona fide research work carried out by then under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma. The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of the degree of Bachelor of technology in accordance with regulations of the Institute.

Dr. Mohammed Rajik Khan
Assistant Professor
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Date:

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Abstract

Success of post-operative and post-traumatic therapy and rehabilitation of conditions related to major joints typically requires continuous passive movement of the affected joint. Physiotherapeutic devices are commonly used to promote rehabilitation of damaged or injured synovial joints. The research work aims to develop an assisted motion device for the physiotherapeutic treatment of the human knee joint. A cam-follower mechanism is proposed to reproduce actual gait cycle with varying flexion and extension of knee joint. The proposed model defines the passive motion device in terms of an improvised range of motion similar to the variation of the knee angle during normal walking gait cycle. Experiments are conducted on the proposed device to verify its angle variation and ease of use for the patients. The intuitive device finds its application in knee joint rehabilitation after knee replacement surgeries, fractures, injuries and other knee joint diseases to facilitate joint flexibility and promote wellbeing. The demonstrated works lays the groundwork for the prospective passive knee models and prosthesis design.

Keywords: Rehabilitation, Continuous passive motion, Physiotherapeutic treatment, Gait cycle

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

One of the primary solutions for major orthopedic knee complications is the knee replacement surgeries. These surgeries, while providing aid for disease like Osteoarthritis, also restrain typical limb movement because of knee stiffness. Knee stiffness can make it difficult to perform certain activities including standing up from a seated position. Stiffness following surgery or injury to a joint develops as a progression of four stages: bleeding, edema, granulation tissue, and fibrosis. Continuous passive motion (CPM) properly applied during the first two stages of stiffness acts to pump blood and edema fluid away from the joint and periarticular tissues. This allows maintenance of normal periarticular soft tissue compliance. CPM is thus effective in preventing the development of stiffness if full motion is applied immediately following surgery and continued until swelling that limits the full motion of the joint no longer develops. This concept has been applied successfully to elbow rehabilitation, and explains the controversy surrounding CPM following knee arthroplasty. The application of this concept to clinical practice requires a paradigm shift, resulting in our attention being focused on preventing the initial or delayed accumulation of periarticular interstitial fluids.

1.1 Problem Statement

The knee joints are one of the most heavily loaded movable joints in the human body and they allow relatively complex motions that enable human motion to take place unimpeded. Various types of reconstructive surgery such as the knee replacement, ACL reconstruction and other knee joint complications leads to knee stiffness. Continuous passive motion (CPM) devices are used during the first phase of rehabilitation following a soft tissue surgical procedure or trauma. The goals of phase 1 rehabilitation are: control post-operative pain, reduce inflammation, provide passive motion in a specific plane of movement, and protect the healing repair or tissue. But the present device performs only a particular common flexion and extension exercise. Bipedal walking is an important characteristic of humans. Hence, after physiotherapy treatment, the human knee regains its flexibility but the habit of the muscles to work in the gait cycle is not regained immediately. We wish to replicate the exact gait cycle biomechanics into the exercise mechanism so that the patient will perform the exact motion of walking during the exercise. So an improvised version of continuous passive motion device replicating the exact gait cycle of the human being is a key challenge to the present researchers.

1.2 Objective of the Work

The objective of the work can be determined as follows:

- To conduct experiment to analyze the human gait cycle and find the motion of the knee joint during the human gait.
- To perform analysis on the data collected and obtain a mechanism to replicate the exact knee movement during the gait cycle.
- To incorporate the mechanism into the continuous passive motion device.
- To collaborate the best features and recreate a CPM device, taking into account the comfort and safety of the user.

1.3 Review of Literature

1.3.1 Knee stiffness

A number of limb complications and various external factors lead to the damage the knee bones of the humans. One of the primary diseases that humans suffer because of these factors is osteoarthritis. It is a degenerative joint disease. Sometimes it even damages the ligaments of the knee joint. The solution of this is to remove the torn ligament and insert a graft. This procedure is otherwise called Anterior Cruciate Ligament reconstruction (ACL reconstruction). Another way to cure arthritis is the complete replacement of the human knee with artificial knee. These reconstructive surgeries lead to knee stiffness in the later stage. Even a knee injury which results in knee immobilization for a prolonged period of time, leads to knee stiffness.

The Four Stages of Stiffness [13]:

- Bleeding
- Edema
- Granulation Tissue
- Fibrosis

The main stage, happening inside minutes to hours taking after articular surgery or injury, is brought about by bleeding, which brings about distension of the joint capsule and swelling of the periarticular tissues [5]. Contingent upon the individual joint, the case accomplishes a most extreme potential volume at a certain joint edge. In the knee, the most extreme limit of the joint capsule has been found to happen at approximately 35° of flexion [4-7]; in the elbow, it happens at 80° of flexion [8]. Greatly high hydrostatic weight is made in the joint and tissues when the joint is flexed or amplified past it greatest limit position while swollen. These outcomes into serious torment and an expanded imperviousness to movement. Instantly taking after damage or surgery to the joint, the characteristic propensity is to hold the joint in the position of most extreme articular volume to minimize painful extention of the joint capsule and the weight of the intra-articular hematoma [7]

The second phase of stiffness, which happens amid the following couple of hours or days, is very much alike however advances less quickly. It is because of edema, brought on by incendiary arbiters that are discharged by platelets and dead and harmed cells. These cause close-by veins to expand and release plasma, bringing about swelling of the periarticular tissues, accordingly decreasing their consistence. With swollen and less agreeable tissues encompassing it, the joint gets to be physically more hard to move and development gets to be more difficult [5 - 8]. As yet, firmness and loss of periarticular tissue consistence are just because of the collection of liquid. In the following two stages, liquid is supplanted by extracellular framework testimony, denoting a noteworthy move [13].

In the third stage, granulation tissue is shaped. This happens amid the initial couple of days or weeks taking after injury or surgery. Granulation tissue is a much vascularized, approximately composed tissue with material properties some place between an exceedingly sorted out blood clump and free areolar stringy tissue [13]. As this granulation tissue shows up inside and encompassing the joint, the firmness already because of liquid amassing gets to be progressively because of the statement of a strong extracellular lattice [13].

Fibrosis is the fourth phase of knee firmness. Thick and unbending scar tissue is shaped in this stage, because of the development of granulation tissue. This scar tissue has a high amassing of collagen sort I filaments in its extracellular network [13].

To solve the problem of knee stiffness the continuous passive motion device (CPM) device is used [13].

1.3.2 CPM device

Continuous Passive Motion is a gadget which is utilized to offer movement to the human appendages and appendage joints as a system for restoration and physiotherapy. This gadget is self-controlled and doesn't oblige the persistent push to grant the movement. This sort of latent movement helps in counteracting joint firmness. In the initial couple of days taking after damage or surgery, CPM is valuable principally to minimize joint hemarthrosis and periarticular edema; additionally it has been has been found to expand the leeway of a hemarthrosis from a rabbit knee [9]. In the vicinity of a joint effusion, development of the knee far from the position of greatest volume and consistence causes an increment in intra-articular weight. The more prominent the emanation, the more noteworthy the weight produced at a certain level of joint flexion [4-8]. CPM causes a sinusoidal wavering in intra-articular weight [10]. This quickens the freedom of a hemarthrosis. The improved leeway of blood from inside the joint and the freedom of blood from the periarticular tissues because of CPM has been archived and measured by following radiolabeled erythrocytes [10].

By adequately pumping liquid far from the range of the joint [9, 11], CPM correspondingly avoids further amassing of edema in the periarticular delicate tissues. Therefore, CPM is of most extreme advantage and significance in the initial couple of hours and days taking after surgery (i.e., the first and second phases of firmness). CPM is less successful in the third phase of firmness and insufficient in the fourth. Supported extending of the periarticular tissues, through the utilization of props, may be required in the granulation stage, and fibrosis might just be agreeable to forceful propping or surgical treatment [13].

1.3.3 Gait cycle

Gait Cycle consists of two main phases: the stance phase and the swing phase. 60% of the cycle is the stance phase while 40% of gait cycle is swing phase. Gait involves a combination of open- and close-chain activities [1].

A more detailed classification of gait recognizes six phases [1]:

- Heel Strike
- Foot Flat
- Mid-Stance
- Heel-Off
- Toe-Off
- Mid-Swing

Figure 1. Gait cycle [1]

An alternative classification of gait involves the following eight phases [1]:

- Initial contact
- Loading response
- Mid-stance
- Terminal stance
- Pre swing
- Initial swing
- Mid-swing
- Late swing

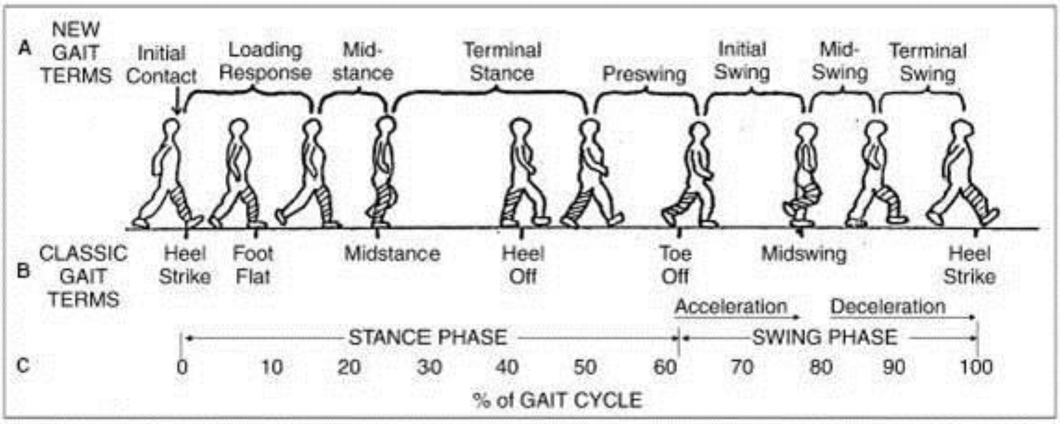


Figure 2. Gait analysis [1]

The heel strike starts the Stance phase. At this moment, the heel begins to touch the ground while the toe is in air. In the mid-stance phase, the foot is settled at the lateral border. During the transition from mid to toe off stance, the metacarpohalanges contract. The toe-off phase is also called the propulsive phase [2].

The swing stage starts when the position stage ends. This stage happens between the toe off stage and the heel strike stage. Two additional stages can be perceived in the swing stage, i.e. speeding up and deceleration. The increasing speed stage goes from toe-off to mid-swing, and the deceleration stage begins from mid swing till heel strike. In the quickening stage, the swing leg quickens forward to impel the body weight in the forward heading. The announcement stage brakes the speed of this forward body development to place the foot down with control. The mid-swing stage happens in the middle of these two stages. In this stage, both feet are under the body, with the heel beside one another [2].

The gait cycle includes movement in every part of the leg (and the body). In the pelvic part there is an anterior-posterior displacement, which substitutes from left to right. This displacement encourages front development of the leg. At every side, there is an anterior-posterior displacement of 4-5° [1, 12].In the frontal plane, different developments is seen in the foot between heel-strike and foot-level and between heel-off and toe-off. A few valgus development is additionally seen between foot-level and heel off in the feet. In the hip, some different developments are seen in horizontal developments. At the point when the abductors are excessively feeble, a Trendelenburg gait can be watched [1, 2]

Underneath we should examine the distinctive developments in the diverse periods of the stride cycle:

Heel strike, otherwise called starting contact, is a brief time which starts the minute the foot touches the ground and is the first period of twofold backing. 30° flexion of the hip and full expansion in the knee is watched. The lower leg moves from an impartial (supinated 5°) position into plantar flexion. After this, knee flexion (5°) starts and increments, generally as the plantar flexion of the heel expanded [3]. The plantar flexion is created by constriction of the tibialis foremost, augmentation of the knee is brought on by a withdrawal of the quadriceps, flexion is brought on by a compression of the hamstrings, and the flexion of the hip is brought on by the withdrawal of the rectus femoris and gluteus muscles [1, 2]. In foot level, or stacking reaction stage, the body retains the effect of the foot by coming in pronation. The hip moves gradually into expansion, created by a compression of the adductor magnus and gluteus maximus muscles. The knee flexes to 15° to 20° of flexion. Lower leg plantar flexion increments to 10-15° [1, 2].

In midstance the hip moves from 10° of flexion to expansion by constriction of the gluteus medius muscle. The knee comes to maximal flexion and after that starts to augment. The lower leg gets to be supinated and dorsiflexed (5°), which is created by some withdrawal of the triceps surae muscles. Amid this stage, the body is bolstered by one single leg. As of now the body starts to move from power ingestion at effect to drive impetus forward [1, 2].Heel off starts when the heel leaves the floor. In this stage, the body weight is separated over the metatarsal heads. Here we would be able to see 10-13° of hip hyperextension, which then goes into flexion. The knee gets to be flexed (0-5°) and the lower leg supinates and plantar flexes [1, 2].In the toe-off/preswing stage, the hip gets to be less amplified. The knee is flexed 35-40° and plantar flexion of the lower leg increments to 20°. In toe-off, similar to the name says, the toes leave the ground [9, 10]. In the early swing stage the hip stretches out to 10° and afterward flexes because of constriction of the iliopsoas muscle 20° with sidelong turn. The knee flexes to 40-60°, and the lower leg goes from 20° of plantar flexion to dorsiflexion, to end in an impartial position [9, 10]. In the midswing stage the hip flexes to 30° (by constriction of the adductors) and the lower leg gets to be dorsiflexed because of a withdrawal of the tibialis front muscle. The knee flexes 60° yet then stretches out give or take 30° because of compression of the sartorius muscle. This augmentation is brought on by the quadriceps muscles [9, 10].The late swing/statement stage starts with hip flexion of 25-30°, a bolted expansion of the knee and an impartial position of the ankle[10].

Various mechanisms were then studied to replicate the human gait cycle.

1.3.4 Study of mechanisms

A four-bar linkage, additionally called a four-bar, is the least complex mobile shut chain linkage. It comprises of four bodies, called bars or connections, joined in a circle by four joints. By and large, the joints are arranged so the connections move in parallel planes, and the get together is known as a planar four-bar linkage. In the event that the linkage has four pivoted joints with axes calculated to converge in a solitary point, then the connections proceed onward concentric circles and the assembly is known as a round four-bar linkage. Bennett's linkage is a spatial four-bar linkage with pivoted joints that have their axes calculated in a specific manner that makes the framework mobile [3]. Reversals of the component are gotten when the altered connection is changed to a free connection and another connection is settled. A solitary four bar mechanism can give diverse sort of movement in view of the connection which is settled.

Inversions of class 1 four bar mechanism [3]

- When link 'b' is fixed: Crank Rocker or Crank Lever mechanism, in the the shortest link rotates 360^{o} whereas the other link oscillates.
- When link 'a' is fixed: Crank Rocker or Crank Lever mechanism, in the the shortest link rotates 360 ^{o} whereas the other link oscillates.
- When link ‘d’ is fixed: Drag link or Double crank mechanism in which the links 'a' and 'b' undergoes complete 360 ^{o} motion.
- When link 'c' is fixed: Double rocker or Double lever mechanism in which no link makes a complete rotation about its joints. In such case it is similar to class 2 four bar mechanisms.

A crank is an arm joined at right points to a turning shaft by which responding movement is bestowed to or got from the pole. It is utilized to change over round movement into responding movement, or the other way around. The arm may be a bowed part of the pole, or a different arm or plate joined to it. A rod is appended to the end of the crank by a pivot, typically called an associating bar. The end of the rod joined to the crank moves in a round movement, while the flip side is typically compelled to move in a straight sliding movement. The term frequently alludes to a human-controlled crank which is utilized to physically turn a axle, as in a bike crank set or a prop and bit drill. For this situation an individual's arm or leg serves as the interfacing bar, applying responding power to the wrench. There is normally a bar opposite to the next end of the arm, frequently with an openly rotatable handle or pedal connected [3].

Slider-crank chain inversion: When one of turning sets of a four bar chain is supplanted by sliding pair, it turns into a slider crank chain. First and foremost inversion is gotten when link 1 (ground body) is settled. Applications- Reciprocating motor, responding compressor and so forth. Second inversion is gotten when link 2 (crank) is altered. Applications- Whitworth quick-return mechanism, Rotary motor and so on. Third inversion is gotten when join 3 (joining bar) is settled. Applications- Slotted crank instrument, Oscillatory motor and so forth. Fourth inversion is acquired when turn 4 (slider) is settled. Application- Hand pump, pendulum pump and so forth [2].

A cam is a pivoting or sliding piece in a mechanical linkage utilized particularly as a part of changing revolving movement into straight movement or the other way around. It is frequently a piece of a turning wheel (e.g. an offbeat wheel) or shaft (e.g. a barrel with an unpredictable shape) that strikes a lever at one or more focuses on its round way. The cam can be a basic tooth, as is utilized to convey beats of energy to a steam hammer, for instance, or an erratic plate or other shape that creates a smooth responding (forward and backward) movement in the follower, which is a lever reaching the cam[3]. Cams are mechanical gadgets which are utilized to produce curvilinear or unpredictable movement of mechanical components. They are utilized to change over rotational movement into oscillatory movement or oscillatory movement into turning movement. There are two connections in particular the cam itself which goes about as an info part. The other connection that goes about as a yield part is known as the supporter. The cam transmits the movement to the follower by direct contact. In a cam-supporter match, the cam as a rule pivots while the follower deciphers or sways. Muddled yield movements which are generally hard to attain to can undoubtedly be delivered with the assistance of cams. Cams are broadly utilized as a part of inside burning motors, machine devices, printing control instruments, material weaving commercial ventures, computerized machines and so forth [3].

Important components of a cam instrument are:

- A driver part known as the cam
- A driven part called the follower
- A outline which bolsters the cam and guides the follower

A wedge cam has a wedge of indicated form and has translational movement. The supporter can either interpret or sway. A spring is utilized to keep up the contact between the cam and the follower. In plate cam, the supporter moves in a spiral heading from the focal point of revolution of the cam. They are otherwise called spiral or circle cam. The follower responds or wavers in a plane ordinary to the cam hub. Plate cams are exceptionally prevalent because of their effortlessness and minimization. Barrel shaped cam, a chamber has a circumferential form cut in the surface and the cam turns about its hub. The follower movement is either swaying or responding sort. These cams are additionally called drum or barrel cams [3].

Followers can be grouped in view of

- Type of surface contact in the middle of cam and follower
- Type of follower movement
- Line of movement of follower

Knife edge follower, the reaching end of the follower has a sharp knife edge. A sliding movement exists between the reaching cam and supporter surfaces. It is once in a while utilized as a part of practice in light of the fact that the little territory of reaching surface results in unnecessary wear.

Roller follower comprises of a tube shaped roller which moves on cam surface. In light of the moving movement between the reaching surfaces, the rate of wear is decreased in correlation with knife edge follower. The roller follower is broadly utilized where more space is accessible, for example, gas and oil motors. Level face follower face is consummately level. It encounters a side push because of the erosion between contact surfaces of follower and cam. Round face follower, the reaching end of the follower is of circular shape which defeats the downside of side push as encounters by level face supporter [3]. In swaying supporter design, the turning movement of the cam is changed over into foreordained oscillatory movement of the follower. Deciphering follower is additionally called as responding follower. The supporter responds in the "aide" as the cam pivots consistently. The spiral follower line of development of the supporter goes through the focal point of the camshaft. The balance follower line of development of the supporter is balanced from the focal point of the cam shaft [3]. In power shut cam follower framework sort of cam-supporter framework, an outside power is expected to keep up the contact in the middle of cam and follower. For the most part a spring keeps up the contact between the two components. The supporter can be a wavering sort or of translational sort. In structure shut cam supporter framework a space or a depression profile is cut in the cam. The roller fits in the space and takes after the score profile. These sorts of frameworks don't oblige a spring. These are widely utilized as a part of machine instruments and hardware.

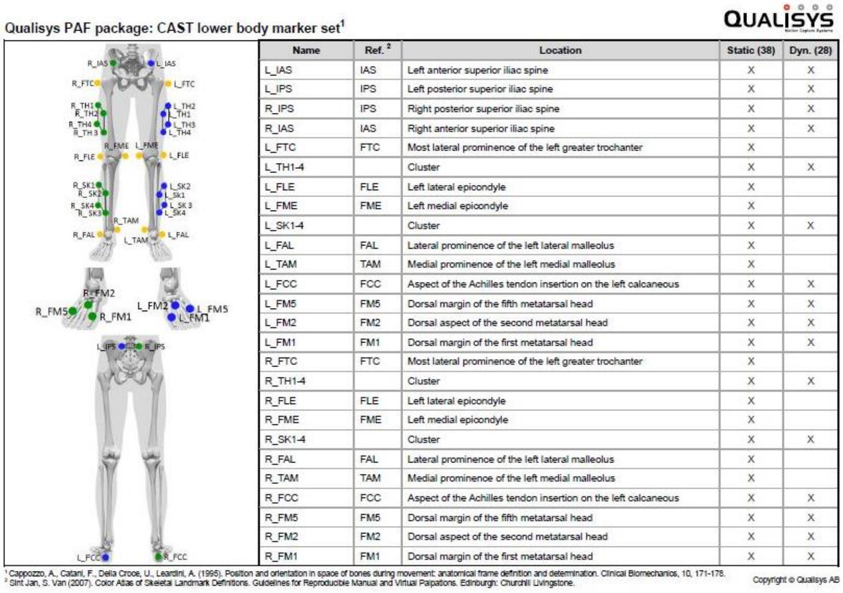
2. Experimentation on Gait Cycle

In this chapter, the biomechanics of human knee for walking on level ground are reviewed. Taking into account the biomechanical functional portrayal of the intact knee joint, the mechanism for replicating the human gait cycle is presented. This mechanism is the used to spur the outline construction modeling of the improvised CPM device.

2.1 Gait Cycle Experimentation

The first step of our project is to study the human knee biomechanics extensively. Gait cycle is the representative period of periodic human walking. The period between successive heel strikes defines a gait cycle for walking on level ground.. The gait cycle of a human subject is studied with the help of Qualysis Motion Capture Systems and then we found out kinetic and kinematic data of a intact subject, at the Applied Biomechanics Laboratory in a study approved by the Biotechnology and Biomedical Engineering Department of NIT Rourkela. One healthy adult male has been taken to study the gait cycle kinetics and kinematics. The subject was requested to walk at a self-chosen speed over a 4m walkway for 10 consecutive trials for normal walking speed and another 10 trials for fast walking speed. He was timed between two fixed points to guarantee that the same walking speed was utilized between test trials. Five percent interval from the self-chosen walking speed was acknowledged. Standard techniques were taken into account for the data collection methods. Four Oqus infrared motion capture cameras were used to measure the three- dimension location of reflective markers at 120 frames/seconds. A sum total of 32 markers were put on foreordained parts of the subject's body using a standard plug-in gait model: 16 lower body markers, five trunk markers, eight upper-limb markers and four head markers just as shown in the Figure below.

Amid walking trials, ground reaction forces were measured synchronously with the kinematic information at a testing rate of the 1080Hz utilizing two staggered force platforms implanted in the walkway. The reaction force of the ground and the center of pressure location were measured by the platforms. Filter frequency was prepared as one entire gait cycle with 100 discrete data points from the heel strike to the following heel strike of the same leg. Joint torques and force were the ascertained utilizing a standard inverse dynamics model.



Qualisys PAF package: CAST lower body marker set[1]

Name	Ref. [2]	Location	Static (38)	Dyn. (28)
L_IAS	IAS	Left anterior superior iliac spine	X	X
L_IPS	IPS	Left posterior superior iliac spine	X	X
R_IPS	IPS	Right posterior superior iliac spine	X	X
R_IAS	IAS	Right anterior superior iliac spine	X	X
L_FTC	FTC	Most lateral prominence of the left greater trochanter	X	
L_TH1-4		Cluster	X	X
L_FLE	FLE	Left lateral epicondyle	X	
L_FME	FME	Left medial epicondyle	X	
L_SK1-4		Cluster	X	X
L_FAL	FAL	Lateral prominence of the left lateral malleolus	X	
L_TAM	TAM	Medial prominence of the left medial malleolus	X	
L_FCC	FCC	Aspect of the Achilles tendon insertion on the left calcaneous	X	X
L_FM5	FM5	Dorsal margin of the fifth metatarsal head	X	X
L_FM2	FM2	Dorsal aspect of the second metatarsal head	X	X
L_FM1	FM1	Dorsal margin of the first metatarsal head	X	X
R_FTC	FTC	Most lateral prominence of the left greater trochanter	X	
R_TH1-4		Cluster	X	X
R_FLE	FLE	Left lateral epicondyle	X	
R_FME	FME	Left medial epicondyle	X	
R_SK1-4		Cluster	X	X
R_FAL	FAL	Lateral prominence of the left lateral malleolus	X	
R_TAM	TAM	Medial prominence of the left medial malleolus	X	
R_FCC	FCC	Aspect of the Achilles tendon insertion on the left calcaneous	X	X
R_FM5	FM5	Dorsal margin of the fifth metatarsal head	X	X
R_FM2	FM2	Dorsal aspect of the second metatarsal head	X	X
R_FM1	FM1	Dorsal margin of the first metatarsal head	X	X

[1] Cappozzo, A., Catani, F., Della Croce, U., Leardini, A. (1995). Position and orientation in space of bones during movement: anatomical frame definition and determination. Clinical Biomechanics, 10, 171-178.
[2] Sint Jan, S. Van (2007). Color Atlas of Skeletal Landmark Definitions. Guidelines for Reproducible Manual and Virtual Palpations. Edinburgh: Churchill Livingstone.

Figure 3. Marker set for lower body gait analysis [12]

Figure 4. Qualysis motion capture system setup

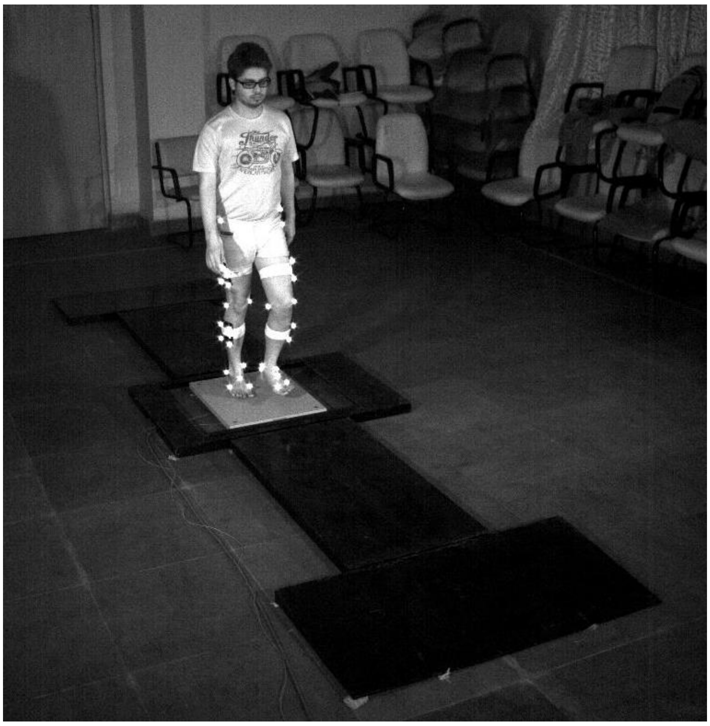
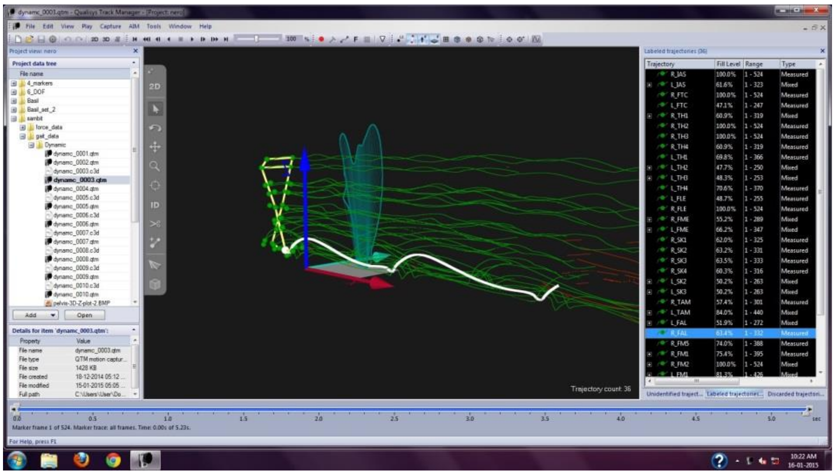


Figure 5. Gait analysis experiment

2.2 Gait Data Collection and Analysis

After the experiment being performed the position of the marker set while walking was captured by the Oqus cameras which were then analyzed to get the trajectory of all the markers using the Qualysis Track Manager as shown in Figure 6.



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File type	QTM motion captur...
File size	1428 KB
File created	18-12-2014 05:12 ...
File modified	15-01-2015 05:05 ...
Full path	C:\Users\User\Do...

Marker frame 1 of 524. Marker trace: all frames. Time: 0.00s of 5.22s.

Trajectory	Fill Level	Range	Type
R_IAS	100.0%	1 - 524	Measured
L_IAS	61.6%	1 - 323	Mixed
R_FTC	100.0%	1 - 524	Measured
L_FTC	47.1%	1 - 247	Measured
R_TH1	60.9%	1 - 319	Mixed
R_TH2	100.0%	1 - 524	Measured
R_TH3	100.0%	1 - 524	Measured
R_TH4	60.9%	1 - 319	Measured
L_TH1	69.8%	1 - 366	Measured
L_TH2	47.7%	1 - 250	Mixed
L_TH3	48.3%	1 - 253	Mixed
L_TH4	70.6%	1 - 370	Measured
L_FLE	48.7%	1 - 255	Measured
R_FLE	100.0%	1 - 524	Measured
R_FME	55.2%	1 - 289	Mixed
L_FME	66.2%	1 - 347	Mixed
R_SK1	62.0%	1 - 325	Measured
R_SK2	63.2%	1 - 331	Measured
R_SK3	63.5%	1 - 333	Measured
R_SK4	60.3%	1 - 316	Measured
L_SK2	50.2%	1 - 263	Mixed
L_SK3	50.2%	1 - 263	Mixed
R_TAM	57.4%	1 - 301	Measured
L_TAM	84.0%	1 - 440	Mixed
L_FAL	51.9%	1 - 272	Mixed
R_FAL	63.4%	1 - 332	Measured
R_FM5	74.0%	1 - 388	Measured
R_FM1	75.4%	1 - 395	Measured
R_FM2	100.0%	1 - 524	Mixed
L_FM1	81.3%	1 - 426	Mixed

Figure 6. Trajectory of the markers during normal walking

On the basis of data obtained from the static marker set on the body of the subject, the bone structure of the subject was created analytically in Visual 3D software. This data was the compared with the dynamic data obtained from the experiment and hence the motion of the skeletal structure was achieved. After the motion of the bones of the lower half body was obtained, the angle between the tibia and the femur was calculated from the Visual 3D software.

div	angle	rad
0	0	0
10	20	0.34906585
14	22	0.383972435
20	20	0.34906585
24	17	0.296705973
26	16	0.27925268
30	13	0.226892803
34	11	0.191986218
36	10	0.174532925
40	9	0.157079633
44	11	0.191986218
46	12	0.20943951
50	17	0.296705973
54	25	0.436332313

56	31	0.541052068
60	43	0.750491578
64	55	0.959931089
66	59	1.029744259
70	65	1.134464014
74	64	1.117010721
76	61	1.064650844
80	52	0.907571211
84	39	0.680678408
86	32	0.558505361
90	18	0.314159265
94	8	0.13962634
96	6	0.104719755
100	0	0

Table 1. Angle between the tibia and the femur during one gait cycle

This data was the plotted in the software to get the graph between the tibia and the femur which is shown in Figure.7.

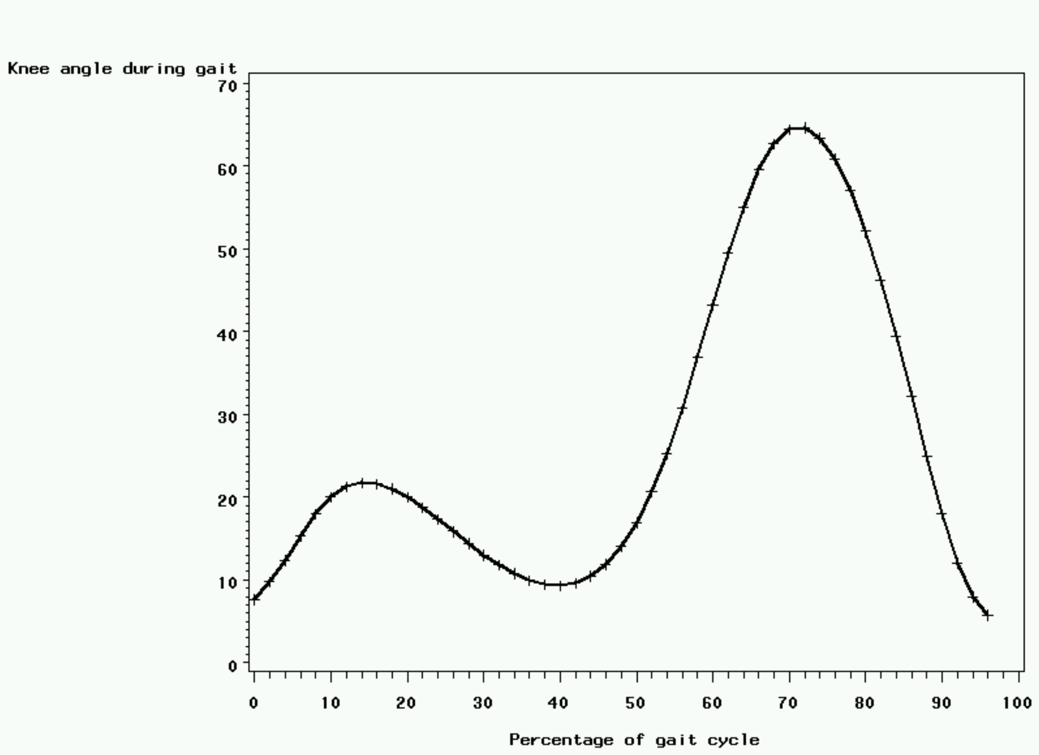

Figure 7. Knee angle vs. Percentage of gait cycle

3. Development of CPM Device

Continuous passive motion (CPM) devices are used during the first phase of rehabilitation following a soft tissue surgical procedure or trauma. Normal CPM device function normal exercises, but here we have tried to bring the exact gait cycle of the knee into the device’s exercise mechanism. This chapter describes the process of creation of a novel mechanism to replicate the gait cycle. Finally an improvised model of the device is created.

3.1 Cam Profile Generation

3.1.1 Generation of concept mechanism

The motion of the human leg is to be replicated basically for the mechanism of the experimental setup. The human leg makes two types of motion, one up and down motion triggered by the knee joint and other is the forward motion triggered by the hip joint, in a complete gait cycle. Thus the mechanism constitutes of a two links connected by a revolute joint. First link is analogous to the thigh part and the second link is analogous to the part below the knee. As the change of angle during the gait cycle is non-uniform in one cycle, hence it was thought to provide that motion by building a cam profile corresponding to the data of the gait cycle and attach it to the lowest part of the second link. To build this mechanism various types of mechanisms were studied. After a thorough discussion the slider-crank mechanism and the cam-follower mechanism were selected.

For the first up and down motion, a combination of the first inversion of the slider-crank mechanism and the cylindrical cam was decided to replicate the up and down motion of the human leg during the gait cycle. The cam is to be placed below the two links of the slider-crank mechanism which will five up and down motion to both the links. The thigh link is fixed at one end and the end of the second link is attached to the cam profile inside a groove. The rotational motion is provided to the cam. Thus the total mechanism gets working. The cylindrical cam was used so that the follower has a constrained motion and will not get displaced from its position. The data for the up and down motion of the leg was collected from the intact subject walking data collection. As per this angle graph obtained the displacement of the lower part of the link from the ground was calculated. Thus we get the height of the lowest part of the link from the ground at each level of the gait cycle. Thus corresponding height of the cam from its center position is obtained for the whole of the gait cycle. Based on this data the cam profile will be generated. For the forward motion the cam needs to move back and forth by some planar joint. For this motion a lot a mechanisms were studied and finally the scotch yoke mechanism was selected to be attached to the center of the cam to give it repeated forward and backward motion. The mechanism is still under conceptual phase.

3.1.2 Numerical Analysis

Subject = Sambit Ghadai

Length of limb = 90 cm (from ground)

Height of ankle from ground level = 49 cm; Weight = 70kg

All the given angles are derived from the gait cycle study.

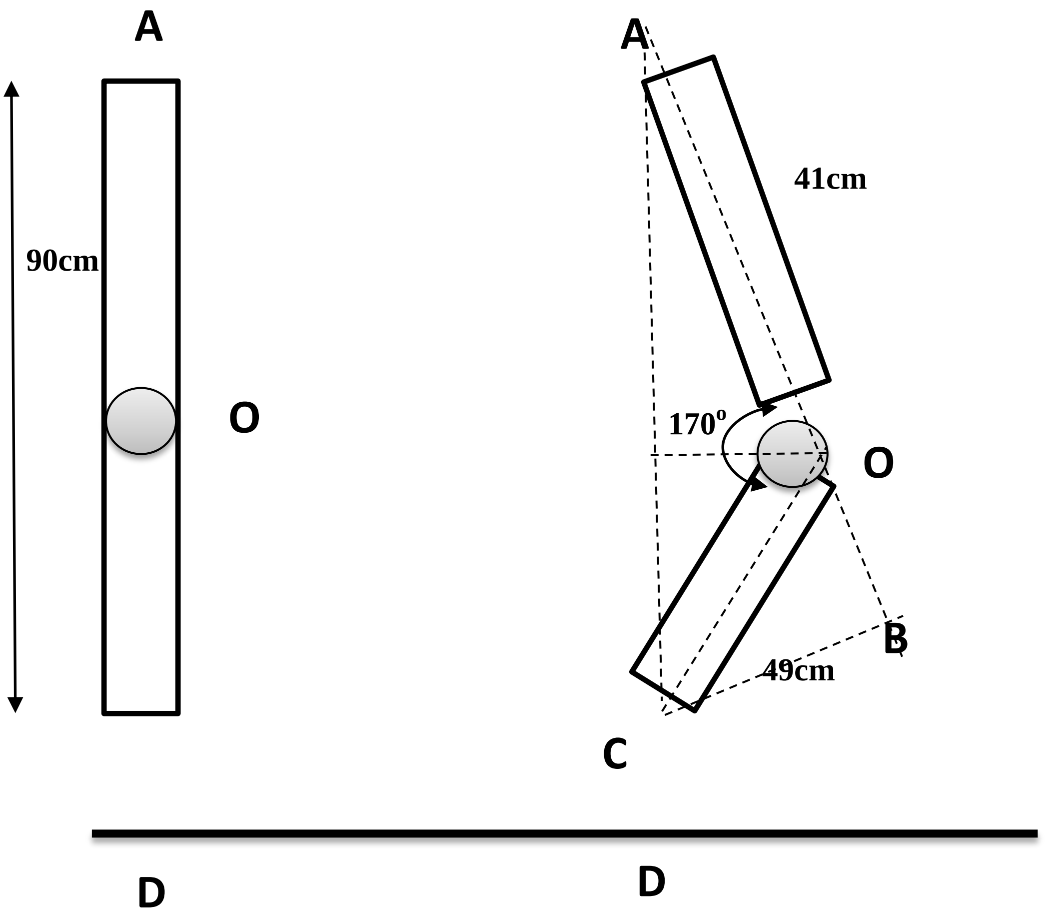

Figure 8. Numerical analysis of mechanism

To find AC –

BC = 49 sin70°

OB = 49 cos70°

So, AB = 41 + 49 cos70°

Using Pythagoras Theorem in ΔACB,

$AC = (AB^2 + BC^2)^{1/2}$

= 74.96 cm

Therefore, CD = 90 – 74.96 = 15.04 cm

3.1.3 Determination of the coordinates of the cam profile

Time (sec)	Angle (degrees)	Time From 0	Percentage of gait cycle	Radian	sinA	cosA	((41+ (49*cosA))^2+ (49*sinA)^2)$^{1/2}$	Dist Heel from Ground
0.26	2.376635	0	0	0.04148	0.041468	0.99914	89.98079691	0.019203094
0.28	4.361337	0.02	1.960784	0.07612	0.076046	0.997104	89.9353382	0.0646618
0.3	6.963761	0.04	3.921569	0.121541	0.121242	0.992623	89.83517881	0.164821192
0.32	9.979997	0.06	5.882353	0.174184	0.173304	0.984868	89.66159098	0.338409022
0.34	12.93522	0.08	7.843137	0.225762	0.223849	0.974624	89.43175213	0.568247869
0.36	15.37854	0.1	9.803922	0.268406	0.265195	0.964195	89.19716738	0.802832616
0.38	16.91726	0.12	11.76471	0.295262	0.29099	0.956726	89.02878703	0.971212967
0.4	17.41402	0.14	13.72549	0.303932	0.299274	0.954167	88.97102578	1.028974218
0.42	17.0097	0.16	15.68627	0.296875	0.292534	0.956255	89.01816394	0.981836059
0.44	15.96759	0.18	17.64706	0.278687	0.275094	0.961417	89.13459101	0.865408995
0.46	14.53741	0.2	19.60784	0.253726	0.251012	0.967984	89.28247034	0.717529663
0.48	12.91622	0.22	21.56863	0.225431	0.223526	0.974698	89.43341862	0.566581378
0.5	11.25187	0.24	23.52941	0.196382	0.195122	0.980779	89.56991476	0.430085242
0.52	9.640546	0.26	25.4902	0.168259	0.167466	0.985878	89.68420651	0.315793488
0.54	8.125106	0.28	27.45098	0.14181	0.141335	0.989962	89.77564593	0.224354072
0.56	6.721317	0.3	29.41176	0.117309	0.11704	0.993127	89.84645225	0.153547749
0.58	5.438091	0.32	31.37255	0.094913	0.09477	0.995499	89.89947556	0.100524441
0.6	4.280546	0.34	33.33333	0.07471	0.07464	0.997211	89.93771137	0.062288634
0.62	3.256545	0.36	35.29412	0.056837	0.056807	0.998385	89.96394658	0.036053415
0.64	2.389606	0.38	37.2549	0.041706	0.041694	0.99913	89.98058673	0.019413268
0.66	1.744387	0.4	39.21569	0.030445	0.030441	0.999537	89.98965479	0.010345209
0.68	1.46356	0.42	41.17647	0.025544	0.025541	0.999674	89.99271756	0.007282445
0.7	1.76107	0.44	43.13725	0.030736	0.030732	0.999528	89.98945597	0.010544031
0.72	2.815206	0.46	45.09804	0.049135	0.049115	0.998793	89.97305612	0.026943882
0.74	4.658674	0.48	47.05882	0.081309	0.08122	0.996696	89.92622222	0.073777778
0.76	7.227578	0.5	49.01961	0.126145	0.125811	0.992054	89.82245831	0.177541688
0.78	10.51388	0.52	50.98039	0.183502	0.182474	0.983211	89.62444287	0.375557135
0.8	14.62137	0.54	52.94118	0.255191	0.25243	0.967615	89.27416975	0.725830249
0.82	19.66017	0.56	54.90196	0.343135	0.336441	0.941705	88.68917213	1.310827873

0.84	25.59647	0.58	56.86275	0.446743	0.43203	0.901859	87.78194671	2.218053291
0.86	32.18044	0.6	58.82353	0.561655	0.532587	0.846375	86.50280211	3.497197891
0.88	38.9756	0.62	60.78431	0.680252	0.628989	0.777414	84.88609519	5.113904809
0.9	45.44241	0.64	62.7451	0.79312	0.712546	0.701626	83.07305554	6.926944455
0.92	51.03425	0.66	64.70588	0.890716	0.777522	0.628856	81.29417295	8.70582705
0.94	55.31564	0.68	66.66667	0.96544	0.822299	0.569055	79.80265378	10.19734622
0.96	58.07314	0.7	68.62745	1.013568	0.848724	0.528836	78.78365285	11.21634715
0.98	59.3167	0.72	70.58824	1.035272	0.860001	0.510292	78.30935195	11.69064805
1	59.17876	0.74	72.54902	1.032864	0.85877	0.512361	78.36241098	11.63758902
1.02	57.79591	0.76	74.5098	1.008729	0.846155	0.532937	78.88814749	11.11185251
1.04	55.24868	0.78	76.47059	0.964271	0.821634	0.570016	79.82683308	10.17316692
1.06	51.60101	0.8	78.43137	0.900608	0.783704	0.621134	81.10312021	8.896879789
1.08	46.96001	0.82	80.39216	0.819607	0.730878	0.682509	82.60944071	7.390559291
1.1	41.45699	0.84	82.35294	0.723561	0.662058	0.749453	84.22174112	5.778258877
1.12	35.21281	0.86	84.31373	0.614579	0.576615	0.817016	85.81824057	4.181759435
1.14	28.36176	0.88	86.27451	0.495006	0.475037	0.879966	87.2794524	2.720547597
1.16	21.1443	0.9	88.23529	0.369038	0.360718	0.932675	88.48439341	1.515606587
1.18	14.02749	0.92	90.19608	0.244826	0.242387	0.97018	89.33186107	0.668138929
1.2	7.714421	0.94	92.15686	0.134642	0.134236	0.990949	89.79774423	0.202255767
1.22	2.964587	0.96	94.11765	0.051742	0.051719	0.998662	89.97012102	0.02987898
1.24	0.32968	0.98	96.07843	0.005754	0.005754	0.999983	89.99963047	0.000369528
1.26	-0.07213	1	98.03922	-0.00126	-0.00126	0.999999	89.99998231	1.76867E-05
1.28	1.389921	1.02	100	0.024259	0.024256	0.999706	89.99343194	0.006568058

Table 2. Distance of foot above the ground during gait cycle

Using the generic formula obtained in the previous section, we determined the height of the foot above the ground during a particular position of the gait cycle. Now implementing the formula on the data obtained from Table 1 will give us the height of the foot above the ground at each position of the gait cycle, which is shown in Table 2.

On obtaining the height of the foot above the ground at each position, we moved a step forward in generating the cam profile for replicating the variation in knee angle during a gait cycle. Considering the cam to replicate one gait cycle in its on whole cycle, we considered the gait cycle to be 100 percent and divided the 360 degrees of the cam as per the percentage. Now we could calculate the height above the ground at each particular degree of the cam, these being the height of the cam from the center at each position we could determine the co-ordinated of a total of 50 points outlining the profile of the cam.

The co-ordinates of those points are shown in Table 3.

degree	radian	X coordinate	Y coordinate
0	0	0	100.192
7.058824	0.1232	12.36829	99.88377
14.11765	0.246399	24.79339	98.57812
21.17647	0.369599	37.34664	96.40279
28.23529	0.492799	49.9977	93.10755
35.29412	0.615999	62.41594	88.17239
42.35294	0.739198	73.91258	81.07824
49.41176	0.862398	83.75457	71.75652
56.47059	0.985598	91.54485	60.65982
63.52941	1.108797	97.26315	48.4313
70.58824	1.231997	101.0829	35.62022
77.64706	1.355197	103.2195	22.60541
84.70588	1.478397	103.8559	9.623669
91.76471	1.601596	103.109	-3.17675
98.82353	1.724796	101.0335	-15.6833
105.8824	1.847996	97.65943	-27.7865
112.9412	1.971195	93.01629	-39.3704
120	2.094395	87.14198	-50.3114
127.0588	2.217595	80.08944	-60.4807
134.1176	2.340795	71.93056	-69.7485
141.1765	2.463994	62.75724	-77.9887
148.2353	2.587194	52.68155	-85.0836
155.2941	2.710394	41.8401	-90.9423
162.3529	2.833593	30.39695	-95.551
169.4118	2.956793	18.51052	-99.0225
176.4706	3.079993	6.265387	-101.582
183.5294	3.203193	-6.38729	-103.559

190.5882	3.326392	-19.7087	-105.432
197.6471	3.449592	-34.2891	-107.786
204.7059	3.572792	-51.0666	-110.997
211.7647	3.695991	-71.0536	-114.755
218.8235	3.819191	-94.7527	-117.749
225.8824	3.942391	-121.521	-117.834
232.9412	4.06559	-149.276	-112.728
240	4.18879	-174.914	-100.987
247.0588	4.31199	-195.383	-82.6983
254.1176	4.43519	-208.626	-59.3593
261.1765	4.558389	-213.815	-33.1903
268.2353	4.681589	-211.018	-6.50141
275.2941	4.804789	-200.871	18.61345
282.3529	4.927988	-184.594	40.42668
289.4118	5.051188	-164.02	57.79836
296.4706	5.174388	-141.241	70.32975
303.5294	5.297588	-118.219	78.33507
310.5882	5.420787	-96.6005	82.76221
317.6471	5.543987	-77.5801	85.10136
324.7059	5.667187	-61.6377	87.07302
331.7647	5.790386	-48.2662	89.88312
338.8235	5.913586	-36.2321	93.52584
345.8824	6.036786	-24.3923	96.98328
352.9412	6.159986	-12.2889	99.24223
360	6.283185	-2.5E-14	100.0657

Table 2. Coordinates of the cam profile

Once the coordinates of the cam profile was obtained in the form of excel file, the cam profile was generated by the help of CATIA V6 software. The excel file named GSD_PointSplineLoftFromExcel present in the command folder of the CATIA software was opened and the appropriate code along with the coordinates of all the points was specified. We have an option of running the macro in excel which transfers all those points along with their respective coordinates into CATIA V6 part as shown in Figure 9. On joining those points using spline we could generate the appropriate cam profile which is shown in Figure 10. The cam generated in the software is shown in Figure 11.

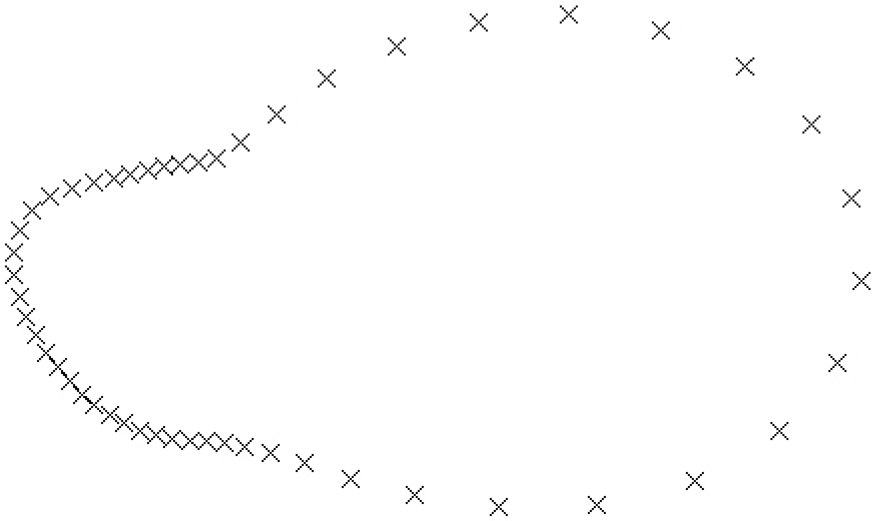

Figure 9. Points specifying the profile of the cam

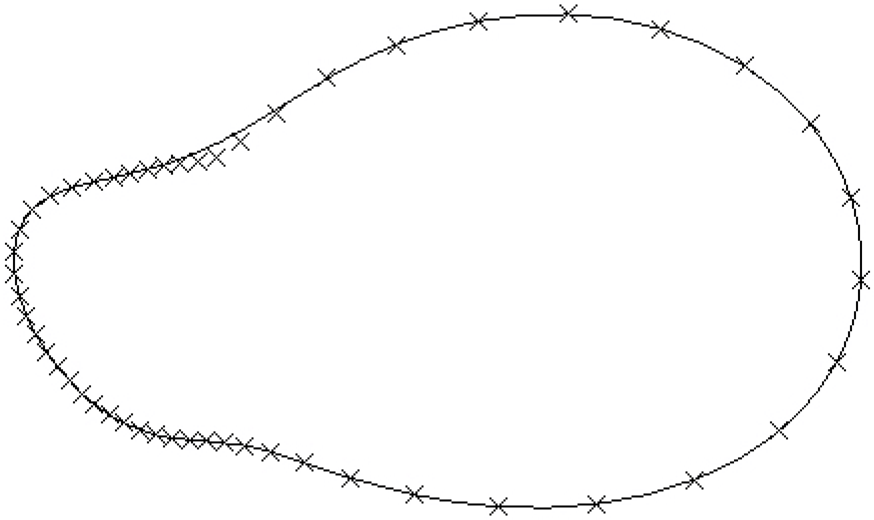

Figure 10. Cam profile

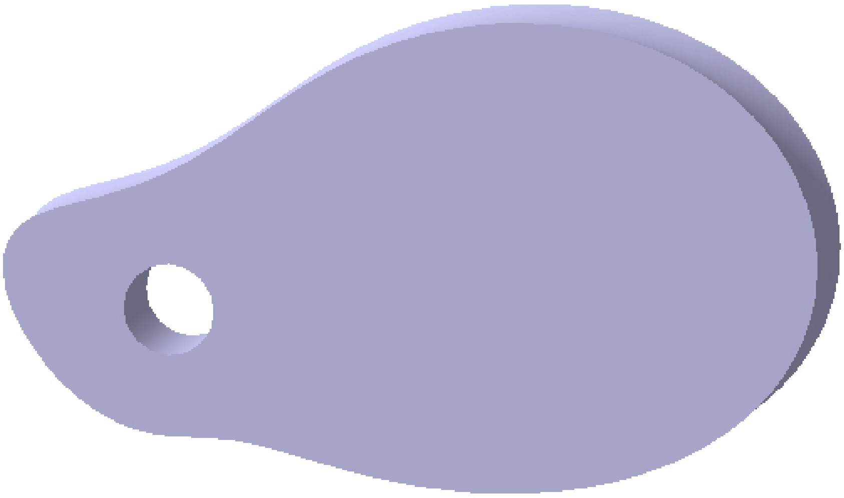

Figure 11. 3D model of the cam

3.1.4 Validation of the cam profile

The cam profile as shown in Figure 11 was generated using CATIA V6 software. A simple mechanism consisting of two rods joined by revolute joint signifying the tibia and the femur was built in SOLIDWORKS 2012 Educational Version. The rod signifying the tibia has a cylinder at its other end which acts a follower to the cam generated. The motor is run for 15 seconds and the angle variation between the two rods signifying the tibia and the femur was plotted in a graph using SOLIDWORKS MOTION STUDY. The graph is shown in Figure 12 and was compared with the graph obtained by experimentation. Both the graph was found to coincide with one another as shown in Figure 13 and hence the cam generated was validated.

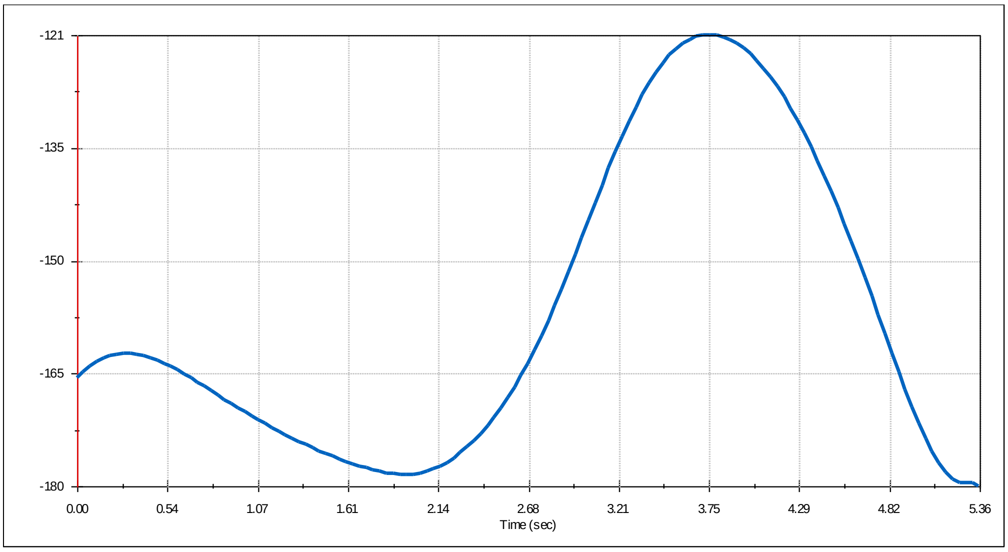

Figure 12. Angle vs. time graph of the mechanism formed by the cam

3.2 Design of the CPM device

CPM device as stated before is a device that is used as an exercise mechanism for the patients recouping from total knee replacement surgery. The main idea of the device was to introduce the gait cycle into the exercise mechanism. The device could be used both for left as well as the right leg. The device will be kept on the ground and the person will exercise on the bed.

3.2.1 Cam design

Since the idea was to replicate the gait cycle mechanism into the CPM device, the cam profile was first generated. The points obtained from the excel file were transferred to CATIA V6 software. The points were joined by spline and then extruded by 20 mm to form the cam as shown in Figure 13.

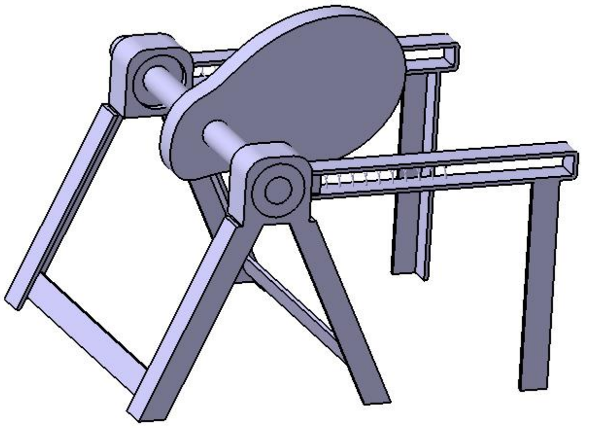

Figure 13. Cam shaft and frame

3.2.2 Motor and Shaft

The shaft diameter is 20 mm and made of aluminum. Ball bearing of standard size 6204zz has been used.

3.2.3 Frame

The frame consists of two v-shaped rods on the ends which support the shaft, motor and the cam. The cam is attached to the center of the shaft. There are two rectangular slots on both the end of the shaft through which the rectangular plate attached to the follower passes to restrict its vertical motion. There are two springs which are attached to the fixed frame one side where as to the plate fixed to the follower on the other end. This helps the follower to be in contact with the cam all the time.

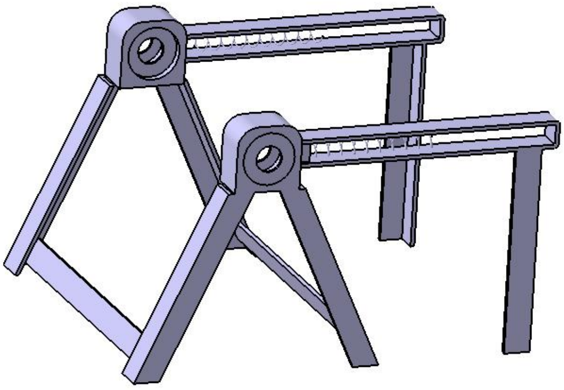

Figure 14. Frame

3.2.4 Follower

The follower is a roller which is fixed to a horizontal plate type structure with three small rods. The horizontal plate passes through the rectangular slots present on the ends of the frame supporting the shaft and the cam. The springs help the follower to be in contact with the cam. The slots restrict the vertical movement of the follower. The horizontal plate fixed to the follower has two vertical rods which are joined to the rods supporting the limb.

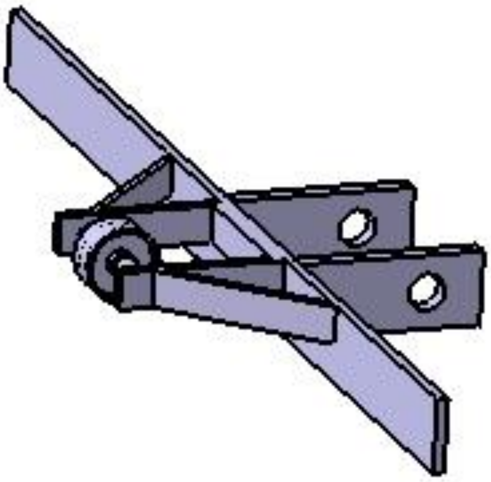

Figure 15. Follower

3.2.5 Limb supporting rods

There are two rods supporting the limb with dimension of 41 and 49 cm respectively. Both the rods are connected by a revolute joint and also by a slider on the bottom. Velcro straps are connected to the limb supporting rods to fix the limbs tightly to the rods. There is also a movable foot rest at the end to rest the foot comfortably.

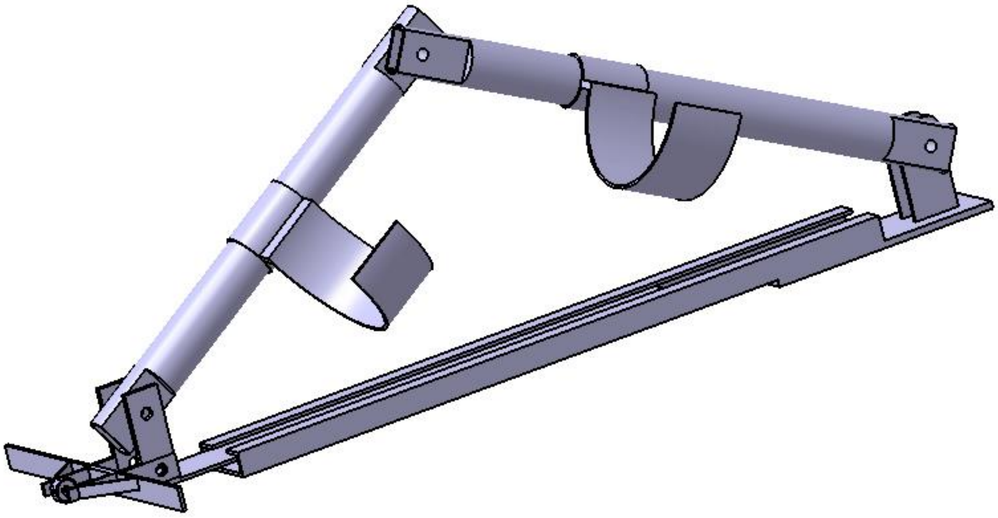

Figure 16. Limb supporting rods

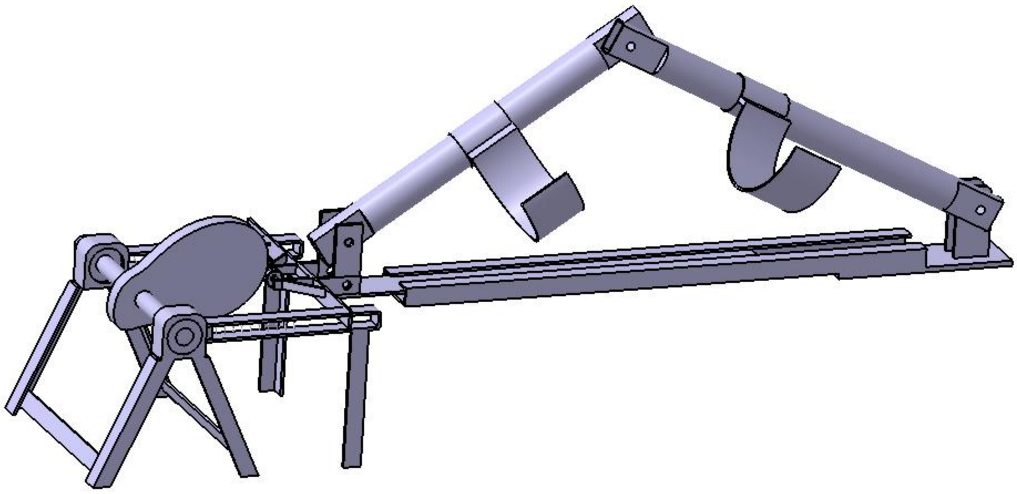

Figure 17. CAD model of CPM device

4. Prototype Development

The prototype is decided to be built of wood and stainless steel parts. The limb supporting rods are to be constructed of aluminum 6061 alloy tubes. The material along with the motor and bearings has been ordered and the prototype development is in continuation phase.

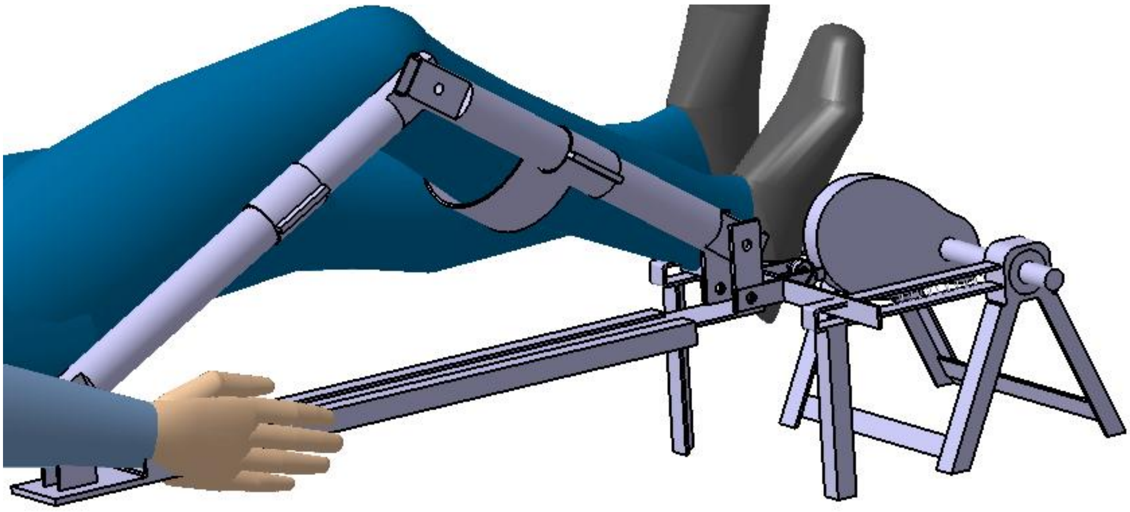

Figure 18. CAD model for prototype development

5. Results and Discussion

The model was designed using CATIA V6 software as per the dimension of the subject used for the experimentation. The model was tested analytically in SOLIDWORKS MOTION STUDY to test the angle variation of the limb supporting rods with the experimental results. The comparison is shown in the Figure below.

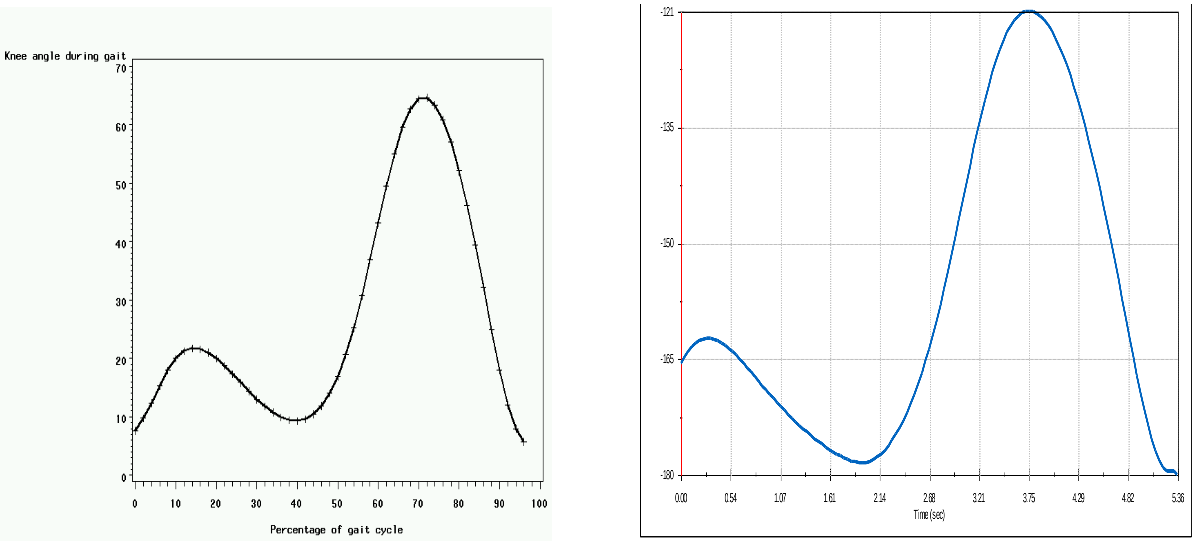

Figure 19. Comparison between the experimental and derived data

The graph obtained from analytical testing is found to be almost same with the experimentally achieved data.

5th, 50th and 95th percentile manikin were placed with the model and the comfort of the manikin was studied at the extremities. The positions of the entire manikin were found to be within the comfort angle range for all the extremity positions.

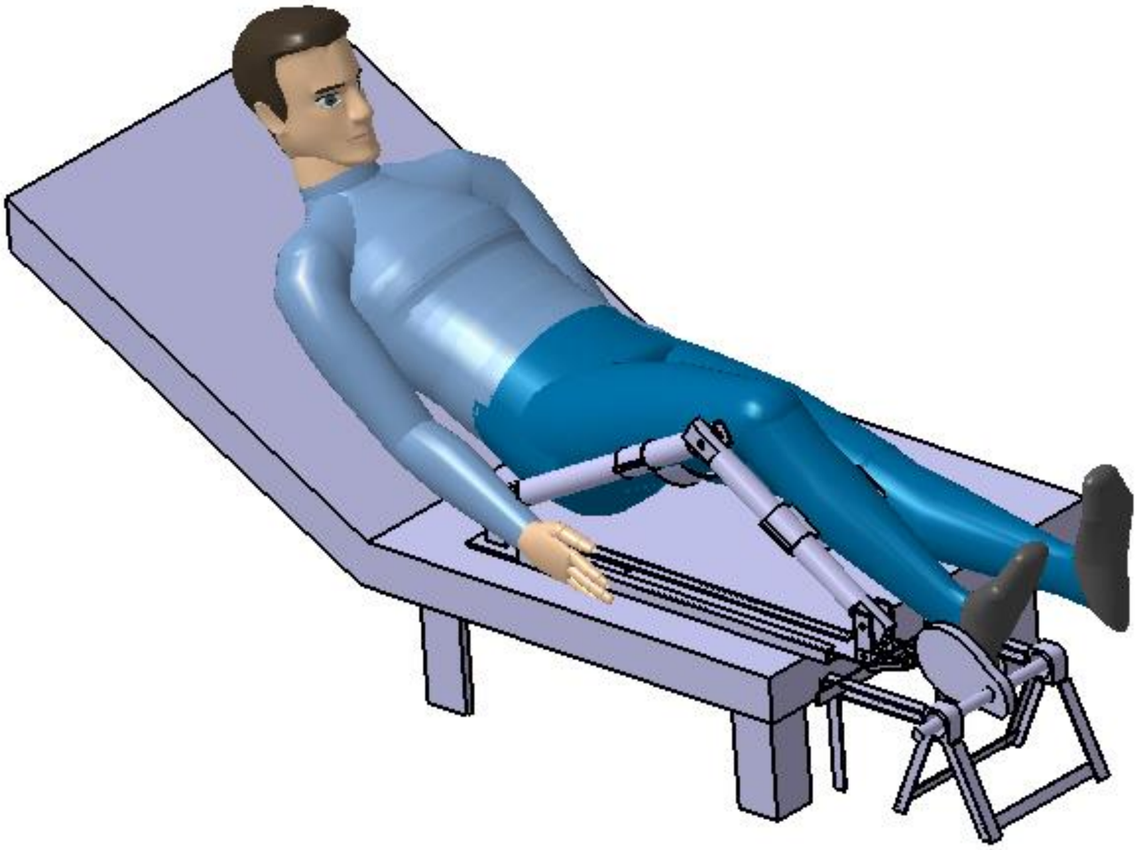

Figure 20. CPM device with manikin

6. Conclusions and Future Scope

This chapter concludes the technical sum-up of the thesis work on the development of a continuous passive motion device following the gait cycle of human knee for the post treatment of knee replacement surgery, which is followed by direction for future work.

6.1 Conclusions

The development of improvised continuous passive motion device is of utmost importance for the patients recovering from the total knee replacement surgery. The main idea of the project was to replicate the knee joint motion during a normal gait cycle into the exercise mechanism of the CPM device. To achieve this experiment was conducted on a subject to find the knee joint variation during a normal gait cycle. A generic formula is derived to calculate the height of the foot above the ground. This formula is used to calculate the coordinates of the cam profile to generate the gait cycle mechanism. CATIA V6 is used to generate the cam profile. The cam mechanism is included in the CPM device and the device is redesigned as per the comfort and feasibility of the patients. Analytical validation is done using SOLIDWORKS MOTION STUDY. The device is tested with the manikin in CATIA V6 to check the comfort of the patient ergonomically.

The implementation of Gait Cycle into the CPM device is for the muscles to get habituated to the Gait pattern. After physiotherapy, there is no need for the patient to undergo further exercise to restore normal walking. The muscles and ligaments of the patient, while undergoing treatment, will also embrace the Gait Cycle simultaneously, so that normal walking resumes easily after treatment.

6.2 Future Scope

The work can be further enhanced by physical testing of the patients with the device and checking the angle variation in practical basis. The cam profile generated and the mechanism used for the device could be used for the creation of passive knee models for study purposes. The mechanism can be used to replicate the motion of the human leg while normal walking. This can be used in robot mimicking human. Prosthesis design can use this mechanism for designing artificial knee for the amputees. The mechanism along with the application of proper muscle and body forces can be also used to develop the simulator for the testing of human knee implants.

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